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Review

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Bioconversion of waste (water)/ residues to bioplastics- A circular bioeconomy approach

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ABSTRACT

Research insight into the technical challenges of bioplastics production has revealed their confoundedness in their niche markets and struggles to enter the mainstream. There is an increasing problem of waste disposal and high cost of pure substrates in polyhydroxyalkanoates (PHA) production. This has led to the future need of upgrading the waste streams from different industries into the role of feedstocks for production of PHA. The review covers the latest developments in using wastes and surplus materials for PHA production. In addition to inexpensive carbon sources, efficient upstream and downstream processes and recycling of waste streams within the process are required to maintain the circularity in the entire process. A view on the link between circular bioeconomy and PHA production process covering the techno-economic, life cycle assessment and environmental aspects has also been provided. Furthermore, the future perspectives related to the topic have also been discussed.

Keywords: Polyhydroxyalkanoates (PHA), Circular Bioeconomy, Recycling, Downstream processing, Sustainability

1. Introduction

Extreme use of non-renewable resources is causing emission of greenhouse gases, and pollution that is contributing towards the degradation of Earth's environment and climate. This is creating a need for new renewable sources for energy and chemicals as replacement options. Another problem existing nowadays is the use of petroleum-based plastics that are not only declining the global oil reserves but also lea ding to plastic pollution due to its waste disposal issues. The so-called "linear economy" is based on the assumption believing that resources are available, abundant, easy to sources and it is easy to dispose the waste (Fernández-Dacosta, 2018). Ryberg et al. (2019) found that around 6.2 million tonnes of macro-plastics (larger than 5 mm) and 3 million tonnes of micro-plastics (smaller than 3 mm) were lost to the environment out of the 322 million tonnes of plastics (excluding elastomers and synthetic fibres) produced globally in 2015 (Ryberg et al., 2019). This can lead to disastrous consequences for example, pollution, contamination in food chain, energy waste, economic loss, endangering biodiversity and increment in the carbon footprint in the environment (Chow et al., 2017). Therefore, a significant shift in industries to experiment new products with super properties is required.

Among them, one of the fascinating group of polyesters is polyhydroxyalkanoate (PHA) that turn out to be an excellent solution to all these problems due to its biodegradability, thermoplastic and mechanical properties. PHAs can be produced by numerous microbial strains using renewable sources under certain unfavourable conditions such as surplus of carbon and limitation of nitrogen, oxygen or phosphorus (Colombo et al., 2016; Koller et al., 2005). The range in their properties can be controlled by the choice of substrate, bacterial strains and fermentation conditions. The plant-derived biomass can be used as a feedstock for their production thus, closing the carbon cycle of the entire process (Dietrich et al., 2017). However, one of the major limitation is very high production cost. The conventionally used polymers cost approx. US$1000-1500/MT while the biopolymers such as PHB prices vary from US$4000/MT to as high as US$15000/MT (Kosseva & Rusbandi, 2018).

In order to improve resource efficiency and waste management, it is important to promote and obey a circular economy approach in the process. Alternatives ranging from biomass, municipal waste streams or industrial waste streams can provide a sustainable carbon source in place of fossil fuels. It will not only help in reducing the waste and waste disposal cost in the environment but also reduce the overall production cost by using wastes as substrates as 30-50% of the total PHA production cost is accounted by the feedstock (Jiang et al., 2012).

Bioplastics are considered highly significant to increase sustainability where sustainability defines a balance between economic, environmental and social aspects of business and can be applied to different domains. Sustainable production of PHAs has to consider the 4 'e' aspects, i.e. economic, ethical, environmental and engineering aspects (Koller et al., 2017) (Figure 1). The feasibility of bioplastics production from wastes of different industries will be considered in the coming sections. One of the important prerequisite for sustainable industrial development is the assessment of the process on the ecosphere. Environmental assessment tools like environmental footprint, and Life cycle assessment (LCA) showed that PHA production can contribute to greenhouse gasses (GHGs) emission reduction (by around 200%), reduction in fossil energy use (by around 95%), waste reduction and incorporation of bio-economy concepts (Dietrich et al., 2017). The review aims at providing a vision covering all aspects and key challenges to ensure circular bioeconomic attitude in PHA production process by development of holistic approaches for a better reuse, recycle and management strategies.

#Insert figure 1 here#

2. Replacement of plastics by bioplastics

Insufficiencies of active solid-waste management to ascertain the plastic refuse generate critical predicaments concerning environment, human and animal health. Consequently, there is substantial inquisitiveness in the elaboration of bioplastics, the biodegradable green plastic substances where one of the foremost elements is a plant, animal or microbial source derivative (Kalia et al., 2000). Polyhydroxybutyrate (PHB) was the first known bioplastic remarked in 1926 by Maurice Lemoigne (French researcher) while experimenting with bacterium *Bacillus megaterium*. The impact of Lemoigne's breakthrough was skipped for a good span of time, seeing that petroleum was ample and economical. The petroleum ruins in-1970s fetched reinstated concern in finding substitutions to petroleum-centred products. The emergence of recombinant DNA technology and molecular genetics further impelled research, which led to the establishment of the structures, production methods, and purposes of several varieties of bioplastics in the current century.

Biopolymers comprise an assorted set of naturally arising polymers such as cellulose, pullulan, starch, alginates, chitosan, and PHA. The chief polymers are obtained from plants, animals or microbiota, especially bacteria which are treated in bioplastics unlike long-established plastics, the petroleum derivative (Vartiainen et al., 2014). The bioplastics commercialization and industrialization on a global scale is governed by the USA and Europe. Commercially, Japan's Fujitsu Laboratories, Ltd., joined hands and came together with Toray Industries Inc., to manufacture several different hardware elements for FMV-Bilbo NB80K range of personal computers and laptops production by applying the usage of bioplastics (Shanaza & Sneha, 2014). However, nowadays starch- and polylactic acid (PLA)-based plastics persist as the prevalent types in the market around the globe. On the contrary, the PHA-based biopolymer market is yet unexplored and is in its initial stages making it a research subject of and interest for the scientists and industrialists globally and will be focussed in the upcoming sections of the review.

The various properties of PHA can vary based on their different sizes of side chains in the repeating units. Also, the polyester types being synthesised is dependent on the microbial strain. PHA accumulates in the cytoplasm of bacteria forming intracellular granules of diameter 0.2-0.7 mm (Girotto et al., 2015). These bio-plastics have several superior properties as compared to conventional plastics and can play an important role in consumer products. Some properties are biodegradability, closed carbon cycle, production using renewable sources, are environment friendly, use less energy, no toxic by-products formation, and low emission of green-house gases. The global PHA market size is expected to reach 23734.65 million tonnes (MT) by 2021, at compound annual growth rate of 6.27% (2016-2021) (Pérez-Rivero et al., 2019).

2.1 Types of Bioplastics:

The research world has developed four scientific ways till date to produce these environment-friendly, sustainable and bio-based plastics i.e., (1) alteration of naturally found polymers (starch, cellulose, pullulan) partially; (2) monomers production involving de novo or fermentation processes from raw materials through conventional chemistry techniques, where polymerization is done subsequently (PLA, polyethylene); (3) production through culturing and adaptation processes of microbial colonies isolated from natural surroundings or developed by genetic engineering (PHA, PHB) (Babu et al., 2013); and (4) production by partially biodegradable polymers like Polybutylene terephthalate (PBT), Poly (butylene adipate-co-terephthalate) (PBAT), polybutylene succinate (PBS) and polyurethane (PU) (Shen et al., 2009). A summary of all the different types of bioplastics along with their commercial uses is given in Table 1.

#Insert Table 1 here#

The category of bioplastics is however studied and divided among three principal groups (Bhatnagar et al.):

1. The conventional plastics generated from fossil resources modified in such a way that they came out to be biodegradable, such as PBAT.
2. The non-biodegradable and partially biobased plastics which includes biobased polyethylene (PE), polypropylene or polyethylene terephthalate (PET) and the bio-based plastics that are technical performers like polytrimethylene terephthalate or thermoplastic polyester elastomer.
3. The plastics which exhibit dual characteristics of being biobased and biodegradable both, for example PLA and PHA.

2.2 Structures and Properties:

Due to their fermentative synthesis, naturally occurring PHAs are precisely isotactic, highlighting the configuration (R) at the chiral stereo centre in the main chain exclusively (Kai & Loh, 2013; Madkour et al., 2013; Reichardt & Rieger, 2011). Although, PHAs are different in terms of their mechanical properties and thus are studied into two sub-categories, (1) PHA_{SCL} with short chain length and monomeric unit containing of five carbon atoms. PHB is considered to be the best representative of this category with a high crystallinity degree (55–80%) (Anastas & Kirchhoff, 2002; Madkour et al., 2013). (2) PHA_{MCL} that are seen as medium chain length wherein the monomeric part has more than five carbon atoms. These PHAs are amorphous macromolecules whose glass transition temperature decreases with an escalation in the side chain length.

The basic features of PHAs could be summarised as, insoluble in water and quite resistant to hydrolytic degradation, tendency of resisting ultra-violet but are unable to withstand acids and bases, dissolve easily in chloroform and other hydrocarbons which are chlorinated, are good for medical usage, facilitate their anaerobic biodegradation in sediments by sinking in water, have no toxicity and are non-sticky when melted unlike conventional polymers (Mannina, 2019).

2.3 PHA synthesis pathways

In bacteria, PHAs are accumulated as high as 90% (w/w) of the dry cell mass as compared to plants [<10% (w/w)] (Steinbüchel & Lütke-Eversloh, 2003; Verlinden et al., 2007). The bacteria used for PHA production can be divided in two groups on the basis of stress conditions required for PHA synthesis. The first group requires limitation of nutrient such as nitrogen, phosphorus, sulphur or magnesium and an excess of carbon source for example, *A. eutrophus*, *Protomonas oleovorans* and *Protomonas extorquens* . The second group including *Alcaligenes latus*, a mutant strain of *Azotobacter vinelandii* and recombinant *E. coli* do not require nutrient limitation for PHA synthesis (Anjum et al., 2016).

PHA are synthesised by enzymatic reactions from acetyl-CoAs catalysed by cytosol located PHA synthases, where accumulation of PHA occurs. The biosynthetic pathway basically consists of three enzymatic reactions catalyzed by three different enzymes. The first reaction is the condensation of two acetyl coenzyme A (acetyl-CoA) molecules into acetoacetyl-CoA by β-ketoacylCoA thiolase (*phbA*). The second reaction is the reduction of acetoacetyl-CoA to (R)-3-hydroxybutyryl-CoA by (R)-specific acetoacetyl-CoA dehydrogenase/reductase (*phbB*). And in the third reaction, the (R)-3-hydroxybutyryl-CoA monomers (direct precursor of PHB) are polymerized into PHB by P (3HB) polymerase (*phbC*) (Muhammadi et al., 2015).

PHB can also be synthesized through de novo fatty acid biosynthesis and β-oxidation pathways from sugars and fatty acids (Aldor & Keasling, 2003). PHA composed of (R)-3-hydroxyfatty acids are synthesized converting intermediates of fatty acid metabolism to (R)-

3-hydroxyacyl-CoA. If the carbon source is oxidized to acetyl-CoA excluding the fatty acid β-oxidation pathway, then fatty acid de novo biosynthesis intermediates are diverted towards PHA biosynthesis catalyzed by the transacylase (*PhaG*) (Hoffmann et al., 2002). If the carbon source is oxidized through the fatty acid β-oxidation pathway, then the (R)-specific enoyl-CoA hydratase (*PhaJ*) catalyses the oxidation of enoyl-CoA to (R)-3-hydroxyacyl-CoA. (R)-3-hydroxyacyl-CoA is a substrate for the PHA synthase (*PhaC)* and the direct precursor of PHA biosynthesis.

3. Application of bioplastics and its commercial products

Bioplastics from PHAs have been commercially developed ever since the 1980s yet the commercial applications are limited. At the commencement of 2003, the rise of oil prices to almost US$ 100 per barrel led to a renewed industrial pursuit for PHAs (Chen, 2009). Subsequently then, different plants opened in China, Italy, the US and Brazil (Table 2). The methodologies vary from raw material choice, bacterial species, and integration in existing bio-processing plants and type of PHA.

#Insert Table 2 here#

Amongst several biodegradable polymers that are still under experimentation and development, PHAs have gained interest due to the fact that their radicals have a great chemical diversity, that deliver the physical properties equivalent to the conventional plastics. The commercial applications of bioplastics derived and produced from PHA are:

a) It is utilized for day to day articles' packaging with a varied range of applications like razors, shampoo bottles (Wella AG), feminine hygiene products, plastic bags, medical garments wore during surgeries, carpets and upholstery (Biomers, P&G, Metabolix and several other companies) (Chen, 2009). It is in fact bioplastics find their major use in the packaging industry.

b) PHA copolymers and blends are competent substitutions to progress process ability and mechanical effects by decreasing the processing temperature and limiting the brittleness of PHAs derived plastics. Till date, PHA heteropolymers and blends have been recommended for food packaging (Fabra et al., 2016).

c) Metabolix established a product selection of additives for polyvinyl chloride (PVC) and PLA, micro powder that can be used for cosmetics, paper and cardboard coatings and denitrification agents made specially for aquariums.

d) TephaFLEX exclusively creates mesh, suture and films for medical usages.

e) Used as nanoparticles for drug delivery and biocompatible porous implants (Shrivastav et al., 2013).

f) It also supports a lot of anti-bacterial properties (Slepička et al., 2016).

g) Newlight Technologies joined hands to replace the cosmetic packaging of all the products from The Body Shop.

h) It helps in the fabrication of scaffolds for tissue engineering (Verlinden et al., 2007).

At the research and experimentation level, probable PHA uses encompass to biofuels in form of the hydroxyalkanoate methyl ester (3HAME), carriers for drug delivery, fine chemical precursors in form of enantiomerically pure monomers in (R)-configurations, health food additives and therapeutic drugs in form of PHA monomers.

4. Need and availability of cheap substrate

Innumerable characteristics mark the swap to bioplastics fascinating as their production utilize almost negligible fossil fuel resources. As per the reports, they also tend to emit less carbon dioxide throughout their life cycle with an advantage of consuming less energy during their production when compared to petroleum derived plastics. They also have minimal health issues related with them and are generally compostable. Undoubtedly, bioplastics have emerged as a fascinating field for researchers but there is always another side of the situation (Kalia et al., 2000). Manufacturing bioplastics on a commercial scale is still expensive which makes them meaningless to both the producers and the consumers. Metabolix produces Mirel bioplastic and Ingeo, made by NatureWorks are commercial bioplastics which have approximately two times more price than that of an analogous petro-plastic (Harding et al., 2007). The cost of bioplastics may fall when the industry expands and better creation methodologies are developed and practiced. However, a shift towards bioplastics may likely influence the cost of raw materials being used. There would be a considerable and hefty price upsurge of the raw materials. For instance, ethanol production influenced the upsurge prices of corn.

Also, the new change of adopting bioplastics is capable to alter the world's food supply in several ways directly or indirectly. Most of the commercial bioplastics available in the global market presently are derivatives of food crops like soy, corn, sugar cane, and several others; which points to the fact that a continuous bioplastics production would directly reduce the amount of these crops availability as food. The situation of food crops availability cannot be solved even by the usage of non-food crops such as switch-grass for bioplastics production as they would subliminally distress food production by striving for land with food crops (Kawamoto, 2007). However, if we use agricultural waste or algae to produce bioplastics, it would have little to negligible effect on the food supply (Dornburg et al., 2003).

To boost the profitability and facilitate its implementation in the plastic market, many operating substitutions and optimizations have been proposed in the laboratory out of which, using industrial by-products and/or waste streams is acclaimed to be one of the most assuring substitutes (Narodoslawsky et al., 2015). The inexpensive substrates are assumed to meet several general requirements, such as, sufficient quantity of feedstock availability, feedstock quality for the whole year ("off-season disposal") remains constant, little or negligible fluctuations in the composition of individual feedstock batches, handling during feedstock collection and transportation becomes easy, storage suitability, no competition with food and feed application.

5. PHA production from waste streams of different industries

The choice of proper raw material for biopolymer production is very important as it can have an additional impact on the ecological pressure caused by the process. For example, it has been observed that PHA production from glucose from corn as substrate negatively contributes to the eco-balance because of photochemical smog, eutrophication and acidification associated with corn cultivation (Koller et al., 2011). Nowadays, wastewater treatment plants are being considered as end of-pipe processes within bio refinery frameworks in endeavours to shift in a circular bio-economic fashion (De Vegt et al., 2012). Therefore, research combining both the industries is under considerations. Table 3 briefly tells how different waste streams as substrates for the microorganisms are being used by the researchers for the production of PHA.

The basic methodology in this regard is to choose renewable, inexpensive and most readily available carbon substrates which will be able to support both the microbial progress and PHA production economically. Several scientific studies have reported and concluded that the microorganisms have the able to recover PHA from various carbon sources ranging from a low-priced, convoluted waste discharges to fatty acids (Eggink et al., 1992) to plant oils (Fukui & Doi, 1998), alkanes (Lageveen et al., 1988) and as well as simple carbohydrates. Waste sources that can be used to produce PHAs are domestic wastewater, food waste, molasses, olive oil mill effluents, palm oil mill effluents, lingo-cellulosic biomass, cannery waste, biodiesel industry waste, waste cooking oil, paper-mill wastewater and sludge, coffee waste, and cheese whey. An important factor for minimizing fuel requirements and gaseous emissions is reducing the distance for raw material transportation and therefore, location of production plant and quantity of available resources has to be also considered. These novel waste-to-product techniques should fulfil certain requirements for their implementation: they should have better ecological profile than conventional production process, they should have sufficient revenue for being economical viable and they should be accepted socially (Fernández-Dacosta, 2018). The economic and environmental benefits of bio-plastics can be coupled with the industrial innovation in terms of production, yield, productivity, downstream processing (DSP) (product separation, purification), and waste stream recycling.

#Insert table 3 here#

5.1 Crude glycerol from biofuel industry:

Biodiesel has emerged as good alternative and renewable fuels and its production capacity has been very well developed in recent years. In the last few years, an increase in the biodiesel production has resulted in a sharp decrease in the glycerol cost, the major by-product of biodiesel manufacturing. Almost 10% of glycerol accumulates considering the quantity of lipids used as feedstock. As a result of which glycerol has gained popularity as an attractive substrate for white biotechnology (Kawaguchi, 2017).

Crude glycerol, a by-product of the biodiesel industry is such a promising carbon source. Crude glycerol majorly is comprised of glycerol, fatty acid ethyl (or methyl) esters, residual ethanol or methanol and residual fatty acids (Ashby et al., 2004). The cells that utilize glycerol remain in a concentrated physiological state because the carbon atoms in glycerol are higher when compared to carbohydrates. These carbon atoms benefit the production by providing the path for the synthesis of intracellular polymer. This directly sums up the fact that glycerol can be used as one of the extremely beneficial substrates for generating PHB precursor acetyl-CoA.

When compared to pure cultures, the use of mixed microbial consortia (MMC) to make PHA is taken up as a potential to promote reduction in the process' environmental footprint. This is necessary because the reduced energy usage is generally linked with minimising the complexities to sustain axenic conditions. However, perception of consuming MMC with organic waste streams as feedstock for PHA synthesis has been proved too (Coats et al., 2008).

Major challenges of producing PHA by crude glycerol comprise of the identification of novel selection criteria for specific production practices and the development of stable processes with less stringent selection criteria. Research studies regarding scheming and dimensioning the amenities and unit set-ups for PHA production on an industrial scale utilizing the crude glycerol phase (CGP) waste stream from biodiesel production are the demand of today's world. With the intention of salvaging expenses for transportation of the substrate CGP, this creation plant ought to be precisely integrated into the existing production lines for biodiesel, where CGP directly accumulates. Accompanying to this, imminent work should emphasis on the polymers production on a bigger scale for thorough evaluation of their biodegradability, process capability, and applicability for fabrication of biodiesel blends and composites with other biocompatible materials.

5.2 Pulp-paper mill wastewater activated sludge:

Economic profits of the pulp and paper industry have made it to be utmost principal industrial sections in the world. Conversely, these mills are encountering challenges with the energy proficiency procedures and supervision of the following pollutants, taking into consideration the environmental opinions and ongoing legal requirements, making it harder for them to comply with stringent environmental regulations. An organic management plant for these industries on an average normally produces heaps of surplus sludge per day (Malmqvist et al., 2004). This is a problematical waste which can signify an appealing prospect if the provided energy and resources in handling could be transformed into value-added derivatives. Also, these mills commonly produce huge amounts of wastewaters, specifically from raw materials derived from virgin processing, that have the possibility to influence the collecting aquatic environment adversely (Pellegrin et al., 1999). The created run-offs, grounded on factors like raw materials consumed and engaged production method, usually have an elevated chemical oxygen demand (COD) and an exhausted biodegradability and beyond 200–300 different organic compounds and almost 700 organic and inorganic compounds (Karrasch et al., 2006). These substrates may also contain non-biodegradable adsorbable organic halogens (AOX), organic materials, phenolic compounds, colour, etc. (Buyukkamaci & Koken, 2010), varying upon the practical pulping procedure, additive chemicals, and the volume of water used. These mills are considered a major source of environmental pollutants.

Some organisms in activated sludge have the ability to accumulate PHA. The improved biological phosphorus removal process depends on the ability of some organisms to convert volatile fatty acids (VFA) to PHA under anaerobic conditions for later use under aerobic conditions. Activated sludge developed underneath effusively aerobic situations may also show considerable PHA storage capacity, particularly if the sludge is proposed to circumstances with substituting high and low organic burden (feast/famine situations). These dynamic conditions add up a selection pressure on the microbes that supports organisms with a capability to ascertain interior carbon reservoirs.

Activated sludge utilized aimed at PHA production is anticipated to be more cost-effectively advantageous than pure culture methods. It is because of the fact that no reactor sterilization is desired and organic material in wastewater can be take into consideration to have a minimal cost. Various analyses have been performed for PHA production with activated sludge taken from the synthetic wastewaters (Takabatake et al., 2000). Anaerobic fermentation can be employed as a pre-treatment to alter innumerable organic compounds to VFAs and subsequently amplify the possibility to generate PHA using wastewater. Since the monomer constituents modifies the physical and mechanical abilities of PHA, the makeup of the VFAs produced throughout fermentation will impact the finalized polymer product.

The quantity of literature details for PHA production utilizing mixed cultures supplemented with the actual wastewaters is nonetheless restrained. Further reports associated with the production of PHA using activated sludge derived directly or indirectly from actual wastewaters is required in an attempt to conclude the feasible possibility of the conception and to recognize characteristics of the procedure that are vital relating to process steadiness, constraint and improvement from outlooks of wastewater treatment and polymer production.

5.3 Whey from dairy industry:

Dairy industries constitute whey, an abundant waste in numerous parts of the world around the globe. Whey production globally varies from 1.15×10^8 tonnes per year to 1.40×10^8 tonnes annually (Peters, 2006). It has dual advantages for PHA production by being a cheap raw material and disposal challenge to the dairy industry because of its excessive chemical oxygen demand (50,000–80,000 ppm) and biochemical oxygen demand (40,000–60,000 ppm).

Lactose, the chief carbon source in whey, may serve as a resource for development and assist in product growth. PHA production from the entire whey lactose is considered to be economical. The usage of excess whey merges a cost-effective benefit with ecological enrichment by transforming the pollutant whey into valuable products.

To incapacitate the challenges during the continual addition of the whey feed in fed-batch cultures, the researchers have engaged a cell-recycle system which says that if β-galactosidase activity of a production strain is not up to the expected higher levels, lactose can be hydrolysed enzymatically or chemically to glucose and galactose as these monosaccharides are converted by many organisms unlike lactose (Povolo & Casella, 2003; Povolo et al., 2010). A detailed report on the PHA production using whey has been concluded in table 3 above.

5.4 Agro-food wastes from food industry:

An augmentation in the population all over the world leads to an augmenting demand for food production and the processing industry linked with it and consequently the generation of food waste in great quantities. This problem is exaggerated because of time-consuming advancement in the development of efficient waste management schemes and amounts for the appropriate treatment and removal of waste. Food waste is a reservoir of complicated proteins, carbohydrates, lipids, and nutraceuticals and can form the raw materials for commercially essential metabolites (Nielsen, 2017).

Agro-food residues can be organized as lignocellulosic biomass, that contain three foremost elements: hemicellulose, cellulose and lignin. Through the choice of accurate microorganism, it is probable to attain by means of fermentation of these sugars a widespread range of metabolites. Lignocellulosic constituents, if possible waste from food and agricultural filtrate (because of their large quantity and zero worth), have been utilized as sources for the development of PHAs and PHB.

Reddy et al. (2012) has also done an optimization experiment on PHA using mixed aerobic and anaerobic cultures and concluded that microenvironment had the maximum consequence on PHA production (Reddy et al., 2012). For impending industrial consumption of PHA-utilizing material, PHA transformation must be scaled-up depending on the use of an adjusted eco-competent MMC depended process that supports to lessen funds and operational costs of PHA conversion with respect to pure culture. Also, the combination of synthesized PHAs and lignocellulosic fibres as bio-composites should persist to be surveyed to customize price and purposes of PHA-based materials to food usage necessities as well as transport, mechanical, and economical properties.

5.5. Factors affecting PHA yield in fermentation:

A number of factors have been reported by various researchers for the variation in the PHA yield, some of them are listed below:

• C/N Ratio: The desired ratio required for the PHA production changes from microbe to microbe. However, it is observed that carbon content should be in excess for better PHA accumulation or else the microbes may start utilizing PHA as a carbon source in carbon limiting conditions, and PHA will be degraded (Bayram et al., 2008).

• Inoculum Size: Reports propose that the increase in organic load is in direct relation to increase in PHB accumulation (Saharan & Ankita, 2012). High substrate availability (feast conditions) takes longer time to store maximum of PHB. Fewer organic loads result in faster PHB production. PHA production aptitude depends on substrate concentration because stored PHB was significantly high at higher substrate loading rate equal to 40.3% of CDW (Reddy & Mohan, 2012).

• Nutrients: Addition of CO_2 either as gas or bicarbonate has shown to increase the biomass productivity (Reichardt & Rieger, 2011). Limiting nitrogen and methane conditions in feast-famine preferred PHA/PHB accumulation (Park et al., 2012). Deficiency of iron subsided the build-up of PHA/PHB (Pérez-Rivero et al., 2019). Addition of sodium provides reducing equivalents for CH_4 oxidation and thus aid in for better PHA/PHB yields (Zhang et al., 2009).

• Mode of fermentation: Two fermentation modes: batch mode and fed batch mode can be carried out for PHA production. With the batch mode, substrate utilization is limited and also C/N ratio cannot be controlled. But with the fed batch mode, substrate utilization is relatively fast as low substrate concentration is provided in beginning and based on consumption, regular substrate feeds are provided and also the C/N ratio can be controlled. Hence, there has been a lower biomass and PHA productivity in the batch mode and higher biomass and high PHA productivity in the fed batch mode (Zhang et al., 2009).

• Operating parameters: The fluctuating paremeters pH and temperature entirely depend on the microbe being used for the PHA accumulation. Based on the studies carried out by Palleroni et al. (PALLERONI & PALLERONI, 1978) and Wei et al. (Wei et al., 2011), the pH range optimal for the survival and good yields of PHA by bacteria is 6.0 to 7.5. The optimal temperature required for the production is 30 to 37°C as per the reports by Yu-Hong Wei et al. (Wei et al., 2011).

6 Downstream processing (DSP) in relation to circular bioeconomy

In order to put the PHA production process in context with the circular bioeconomy, the entire process has to be considered. These bioplastics should perform better than conventional plastics in regard to the overall environmental impact. DSP constitutes a substantial part in the entire production process of PHA and an efficient and sufficient extraction of PHA from microbial biomass is crucial. Broadly categorizing there are two ways of recovering PHAs after fermentation, either dissolving the biomass to separate PHA granules using acids, alkali, surfactants, enzymes or extracting PHAs directly from the biomass using solvent that can change the permeability of cell membrane and dissolve the polymer inside the cells (Kosseva & Rusbandi, 2018). Various optimisation is required in these steps in order to get the desired PHA concentration and purity. For example, if the concentration of oxidant is not controlled it could lead to the dissolution of PHA also along with non-PHA cell mass (NPCM) leading to low recovery of PHA or using solvents may destroy the natural morphology of PHA granules which is required for the production of strong fibres. This NPCM can also be converted into value-added product in a sustainable way. Research in the anaerobic digestion of NPCM in biogas plant or hydrolysis (chemical or enzymatic) of NPCM to carbon- and nitrogen rich source for subsequent microbial cultivation batches is in progress. NPCM can also be used a green fertilizer in agriculture (Kosseva & Rusbandi, 2018).

The step of PHA recovery can constitute as an important factor in the cost and also, have a significant impact on the ecological footprint of the entire production process. For example, halogenated PHA extraction solvents such as chloroform, dichloromethane etc. though show a high extraction yields and product purity but in addition to high costs, they show high risk not only to environment but also for the people working with them. Therefore, it is crucial to focus the research on new extraction processes using recyclable solvents that are environment-friendly such as lactic acid esters (Koller et al., 2011).

Techniques without the excessive solvents such as ultrasonication, and enzymatic digestion can be feasible for the quantitative release of PHA granules. However, the granules obtained can be covered with membranes that have to be removed for polymer purities or their medical application (removal of lipopolysaccharides that are endotoxins). This will cause additional purification steps, increasing the costs of the DSP. All these methods have some disadvantages in terms of economy, ecology, safety aspects, PHA yield, product purity, and scaling difficulties. The selection of the PHA recovery steps is determined by factors such as PHA producing strain, product purity requirement, availability of separation materials or techniques, and acceptable molecular mass of biopolymer. The application of minimizing the amounts of solvents and other cost-impacting compounds/techniques have to be applied at industrial scale.

Recent developments in PHA recovery have been done that involve application of harmless solvents, ionic liquids or supercritical fluids. However, even with intensive research on PHA, DSP is still limited. Various studies have been done to extract and separate PHA using ionic liquids. However, in the process, the processing time is comparatively higher and to reduce it, gentle heating, agitation, sonication, radiation energy, pressure can be applied but it will further increase the cost of separation. Supercritical fluids have also attracted attention amongst researchers due to its availability, non-toxicity, low reactivity and non-flammability characteristics. This method can give the PHA with purities 86-99%. However, capital and maintenance costs are the disadvantages in this method. Mannina et al. (2019) used switchable anionic surfactant (SAS) for PHA recovery from MMCs (Mannina et al., 2019). They showed an economically convenient way to avoid extra consumption and PHA loss during high doses for specific purposes. SAS can be simply recovered by using CO_2 as pH-trigger. They can be directly and reversibly converted into less soluble form so they can be removed from liquid phase and recovered to be reused afterwards. Koller et al. (2013) discussed ecological and economic benefits by combining the production technology with double optimisation procedure. They showed the importance of raw and axillary materials selection, production steps, extraction process, logistics, and equipment along the production process and the entire life of the product (Koller et al., 2013). The high impact of the production process of PHA on environment resulted from the high mechanical energy requirements and low yield of PHA produced.

Therefore, development of efficient recovery methods is very important for the overall bioeconomics of the PHA production process. The choice of efficient extraction methods is based on various parameters such as cost, ability to maintain the molecular weight of PHA, environment friendly process, economically feasibility, sustainability, and energy requirements. Therefore, with the fermentation process and its optimisation studies, PHA recovery techniques should also be considered.

7 Waste stream recycling

The increase in PHA production can also be achieved via feed forward method. In this, recycling is done by contacting the biomass obtained in the previous reaction cycle from which the PHA was extracted to the culture of the next reaction step. This technique will induce the culture to convert the carbon within the PHA-reduced biomass into PHA. It is advantageous because it avoids the need for new biomass therefore, reducing carbon requirement (Kosseva & Rusbandi, 2018). The residual bacterial biomass (RBB) is comprised of lysed bacterial cells comprising of nucleic acids, proteins, carbohydrates and lipids. Wei et al. (2015) used the RBB and converted it into bio-oil and biochar by pyrolysis. The bio-oil and biochar yield was obtained 28 and 48% respectively (Wei et al., 2015). The compounds identified in bio-oil were hydrocarbons, phenolic compounds, aliphatic ketones, nitrogen and oxygen containing aromatic compounds, aliphatic compounds, amines and carboxylic acids. The study basically showed that RBB can be used to produce co-products to improve PHA economic practicality. Also, nitrogen-rich pyrolysis oil could be used as a potential feedstock for the production of PHA.

Recycling of the major waste stream from PHA production is not only important cost factor but also is of major importance for minimization of the environmental load. Therefore, impact of reutilizing these side waste streams can constitute a major part in future activities for industrial PHA production. After the cell-disruption, proteins and other cell components are released. Proteins counting to be approximately 50% of the dry weight of bacterial cells, these proteins released could either be recovered by precipitation that could be used as animal feed or the waste stream containing the protein could be used as nitrogen source for the next batch of fermentation (Gherghel et al., 2019). The main stages for protein recovery after cell disruption include filtration, protein precipitation from protein solution and drying of the protein precipitate. However, using these proteins as animal feed can be inconvenient in case the heavy metals are recovered along with proteins and removing them will in turn increase the DSP cost (Gherghel et al., 2019).

Koller (2015) produced PHA from whey of dairy industry by extreme halophile *Haloferax mediterranei* and recycled the waste stream to be used in the subsequent production processes (Koller, 2015). He showed that the spent fermented broth could be used to replace a considerable part of fresh saline fermentation medium in the next production process. Also, 29% of the yeast extract for nitrogen and phosphate source for efficient cultivation of microbes could be replaced by cell debris from previous cultivations. The study provided strategies to combine the reduction of costs with minimising the ecological risk by recycling the waste stream generated and thus, maintaining circularity in the gap present in the system. The adaptation of such extremophiles (*H. mediterranei* to high salinity) offers the advantage of running the process at low operation costs i.e. low energy for sterilisation, less or no solvents requirement for product recovery (because of high inner osmotic pressure).

8 Techno-economic analysis

It is important to include techno-economic evaluation for PHA production using waste sources to understand the process in context with the circular economy. Techno-economic studies would reveal industrial feasibility of any process along with major process parameters that impact the production cost. It reveals bottlenecks of a process and guides the researchers for developing a cost-effective process from industry point of view.

In one of the studies, *Haloferax mediterranei* was used for PHA production using waste stillage of rice-based ethanol industry (Bhattacharyya et al., 2015). PHA concentration of

13.12 g/L with 63% (w/w) PHA content were obtained in 135 h. Desalination of the spent stillage medium occurred in a cylindrical baffled-tank with an immersed heater and a stirrer holding axial and radial impellers. The salts were recovered during (99.3 %) desalination and re-used for PHA production. The cost of PHA was estimated at US$2.05/kg for annual production of 1890 tonnes. Desalination was most cost impacting factor.

In another study, PHB using *Cupriavidus necator* as the micro-organism and citric molasses (waste) as carbon source for fermentation (Pavan et al., 2019). Biomass concentration of 61.6 g/L with PHB content of 68.8% was obtained in cultivation time of 42 h. Techno-economic analysis revealed that if PHB concentration is increased in fermenter from 42.5 g/L to 96.6 g/L through various process modification strategies, the unit upstream processing cost (plant capacity 2000 tonnes) will decrease from 1.62 $/kg PHB to 0.93 $/kg PHB, respectively while unit production cost will decrease from 4.28 $/kg to 3.5 $/kg. The results indicate that PHB concentration in the fermenter is major cost impacting factor.

PHB has been produced using industrial wastewater containing microbial community while extraction has been conducted using surfactant-hypochlorite chemical treatment (Dacosta et al., 2015). Techno-economic evaluation revealed that unit production cost was $ 1.72/ kg PHB. Downstream cost accounted for 73% of total cost while utilities cost accounted for 51% of total cost. LCA revealed that GHG emission was 1.97 kg CO_2-eq/kg PHB and non-renewable energy use (NREU) of 108.54 MJ/kg PHB. While PHB production using commercial substrates for different microbes varied from 1.65-6.4 $/kg PHA while GHG emission varied from 3-5 kg CO_2 eq/kg PHA and NREU was around 81 MJ/kg PHA. The advantage for using mixed microbial community for PHA production is that there is no requirement for sterilization of bioreactor saving the steam cost required for sterilization.

PHB production using mixed methanotrophic culture has been reported with recovery through acetone-water solvent extraction (Levett et al., 2016). Techno-economic evaluation revealed that unit production cost was estimated to be 4.1-6.8 $/kg PHB which was lower than average cost of $7.5/kg from other studies. Contribution of raw material cost in operating cost decreased from 30-50% to 22% indicating methane as effective and low-cost carbon source. Energy consumption for biomass drying was identified as major cost imparting factor. For PHB extraction and recovery, acetone loss needs to be optimized. If PHB producing thermophilic methanotrophs are isolated and used, unit production costs may lower to 3.2-5.4 $/kg PHB.

Four different carbon sources were evaluated for PHA production using *C. necator*: soybean oil, waste cooking oil (WCO), refined and crude glycerol (Leong et al., 2016). PHA concentration obtained at 72 h for different substrates were 20.73 g/L, 11.05 g/L, 31.07 g/L and 25.01 g/L respectively. PHA extraction was done by using chloroform and ethanol. The unit production cost for these substrates were 1.63, 1.18, 0.48 and 0.36 US$/kg PHA, respectively. The study concluded that crude glycerol was most optimum substrate for PHA production while PHA production cost was highly sensitive to PHA yield during fermentation and cost of carbon substrate.

For upstream processing for PHA production, major cost impacting parameters are PHA productivity, PHA content, PHA yield (with respect to carbon substrate) and carbon substrate cost. Using household or industrial waste reduces carbon substrate cost while mixed microbial community doesn't require sterilization. However, PHA content is the most important parameter because it impacts final PHA yield and downstream process efficiency. PHA production cost is also sensitive to plant capacity. In one of the studies when PHA plant capacity increased from 2000 tonne/ year to 10000 tonne/ year, unit production cost decreases from $4.29/kg to $2.71/kg (Pavan et al., 2019). The manufacturer should have idea about plant capacity and market demand besides the process parameters.

Techno-economic evaluation of PHB production process was conducted where *Cupriavidus necator* was used as the micro-organism, citric molasses (waste) was used as carbon source for fermentation (Pavan et al., 2019). In the study, four alternatives for pre-treatment of fermented biomass were studied before being extracted with propylene carbonate as solvent. Four pre-treatment methods of fermented biomass studied were ultrasonication (10 kHz), thermal pre-treatment (95^{o}C for 45 min), high pressure (90 MPa) and no pre-treatment. The final PHB extraction efficiencies for different pre-treatment methods were 92.2%, 92.1%, 97.8% and 81.7% respectively. The unit production cost of PHB for different pre-treatment methods were 4.46 $/kg, 4.28 $/kg, 4.28 $/kg and 4.72$/kg respectively. High pressure and thermal pre-treatment were most economical pre-treatment methods in DSP of PHB.

In another study, PHB was produced using mixed microbial community (Fernández-Dacosta et al., 2015). For DSP, 3 routes were evaluated: a) chemical treatment of cell biomass with 0.2 M NaOH and 0.2% (w/v) surfactant b) chemical treatment with surfactant and NaOCl (sodium hypochlorite) and c) chemical treatment with dichloromethane (solvent). Techno-economic evaluation revealed that alkali treatment was most favourable with unit production cost of $1.54/kg PHB while solvent based treatment was least favourable with unit production cost of $2.15/kg PHB.

9 Tools for sustainability assessment

There are several tools for assessment of sustainability and among them LCA is the most common tool. LCA assesses environmental impacts associated with any manufacturing process from raw material procurement to disposal or recycling. It is also known as "cradle-to-grave analysis" and the concept is used to optimize the eco-design or environmental performance of the product or process. It reveals the major process steps or inputs that impart high GHG emission or has high energy input and is helpful for researchers, decision-makers, policy-makers. However, literature shows that the attempts to find and quantify the environmental impact of PHA production via LCA tools focusses on isolated aspects of production such as only bio-polymer production or energy requirements or only CO_2 emissions which may sometimes not be in agreement with each other (Koller et al., 2011). Therefore, studies analysing the complete process and all the parameters in the process have to be established.

9.1 LCA of upstream processing

PHB has been produced using industrial wastewater containing microbial community (Dacosta et al., 2015). LCA revealed that GHG emission was 1.97 kg CO_2-eq/kg PHB and NREU of 108.54 MJ/kg PHB. Among them, GHG emission of upstream processing accounted for 40% of total and NREU of upstream processing (USP) accounted for 28% of total energy use. While GHG emission for PHB production using commercial substrates for different microbes varied from 3-5 kg CO_2 eq/kg PHA and NREU was around 81 MJ/kg PHA.

LCA of USP is highly dependent on raw material used for PHA production. Among several raw materials, corn starch used for PHB production, soybean oil, sucrose, biogas and municipal organic wastes, corn starch had lowest GHG emission (-2.3 kg CO_2-eq./ kg PHB) and NREU (2.5 MJ/kg PHB) while biogas had highest GHG emission (942 kg CO_2-eq./ kg PHB) and NREU (43.52 MJ/ kg PHB) (Kookos et al., 2019). Moreover, corn starch had lowest acidification potential (0.81 moles H^+ eq.) and eutrophication potential (1.14 g N-eq). Waste substrates certainly have advantage over commercial substrates in terms of environmental impact. Employing waste substrates reduces burden on treatment plants and their disposal reducing GHG emission.

9.2 LCA of downstream processing

LCA for PHA extraction using dimethyl carbonate (DMC) has been performed and compared with halogenated hydrocarbons (Righi et al., 2017). It was found that environmental performance of DMC based extraction is better than those with halogenated hydrocarbons. Four scenarios were considered using DMC protocol: extraction from microbial slurry or from dried biomass, and recovery by solvent evaporation or polymer precipitation. It was found that extraction from dried biomass and PHB recovery by precipitation is always the most promising.

LCA of several DSP revealed that sodium hypochlorite digestion had highest carbon foot print (29.46 kg CO_2 eq/h) as compared to treatment with NaOH or H_2SO_4 (4.08 kg CO_2 eq/h and 6.27 kg CO_2 eq/h respectively) (Dietrich et al., 2017). NaOH treatment had lowest recovery costs 1.12 $/ kg PHA followed by sulphuric acid treatment (1.22 $/ kg PHA) and sodium hypochlorite treatment (5.75-7.27 $/kg PHA). All treatments cause reduction in polymers' molecular weight when compared to traditional chloroform extraction. Among all extraction methods, sulphuric acid treatment was most promising one with high purity (98%), recovery (79%) and low GHG emission (Dietrich et al., 2017).

In one of the studies, three DSP routes were evaluated: a) chemical treatment of cell biomass with 0.2 M NaOH and 0.2% (w/v) surfactant b) chemical treatment with surfactant and NaOCl (sodium hypochlorite) and c) chemical treatment with dichloromethane (solvent) (Fernández-Dacosta et al., 2015). LCA revealed that alkali treatment had lowest GHG emission of 2.4 kg CO_2-eq/kg PHB and NREU of 106 MJ/kg PHB while solvent based treatment had highest GHG emission and NREU of 4.3 kg CO2-eq/kg PHB and 156 MJ/kg PHB, respectively.

Several authors have demonstrated and concluded that PHA production using pure glycerol as substrate with monoseptic cultures does not have much environmental advantage over conventional plastics because of the high energy consumption throughout the production process thus, it is an important contributor in the process. Therefore, it important to identify the ecological hot spots in the process. One of the tool by which it can be performed is Sustainable process index (SPI) that shows important parameters significant to ecological pressure of PHA production such as process yield, energy consumption and release of CO_2 (Koller et al., 2011). Energy consumption is one of the main contributors of ecological pressure in the process and the other factor i.e. the process yield defines the burden on the amount of product by the pressure caused by the process.

Another model tool for environmental assessment is the Cleaner Production tool which focusses on minimizing waste and emissions and maximize output. Industries could analyse flow of materials and energy and identify the points of improvements such as use of materials, avoidance of formation of wastewater, waste streams, surplus heat and gaseous emissions. The concept reveals that the production of PHA has to be performed in zero-emission process i.e. no wastewater release, no global warming gases emissions and no solid waste (Koller et al., 2011). However, experience and knowledge are required to apply the Cleaner Production principles to biotechnology applications especially in the field of PHA production. This will help the future PHA production processes to be optimized, saving energy and minimizing waste. Such studies and tools serve a great help in indicating the introduction of bioplastics production into the sustainability patterns. These strategies discussed should be connected to obtain the global aim of sustainable development (Figure 2). Other sustainability assessment tools that are being used for such studies are carbon footprint, carbon efficiency, health and safety score cards and biomass utilisation efficiency.

#Insert figure 2 here#

10 Integration in biorefineries

Considering our financial system and employing circular resource supervision practices will support alleviate the demanding setback of urban waste management and the controlled accessibility of resources. The insufficiency of supplies will spread in the prospect and the capability to pull through and handle these resources will develop essentially for a balanced global budget (Tonini et al., 2013). A connecting link concerning waste and sectors related to production is required to acquire a sustainable advancement; this can be attained by pertaining waste fractions as aid to industrial production usages concurring to the theory of industrial ecology. Technologies that concern biomass as a substrate for yielding bio-based products are mentioned to as biorefineries. Waste-related biorefinery views consuming side streams from agriculture and the food processing e.g. from bakeries and breweries have acknowledged substantial consideration in current years.

An countenance of significance in prevailing energy and material recovery technologies utilizing waste feedstock often attempt to integrate processes along with remediation (Mohan, 2014; Venkata Mohan, 2014). A biorefinery is a feature comparable to the petroleum refinery, which assimilates biomass conversion methods and technologies to yield fuels, power and chemicals (Soetaert, 2009). The exclusive configuration will be shaped by the environment of the following four types: input raw material; method technologies; platforms (intermission materials like platform chemicals); and the output commodities that are necessitated (Luguel, 2011). However, human consumption of biogenic materials or biomass as feedstock is not new; but nowadays there is a new interest in effective exploitation of unavoidable organic wastes, sparked by the aim to reduce eco-footprint and achieve a more secure supply of renewable resources.

On the other hand, to substantiate environmental claims, the impacts of bio-based materials should be typically quantified by applying LCA to evaluate the potential environmental impact of products and services. Other environmental systems analysis tools include Environmental Impact Assessment (EIA), Ecological Risk Assessment (ERA) and Material Flow Analysis (MFA). In general, environmental systems analysis tools examine social, technical and natural systems and the links between these systems (Baumann & Tillman, 2004).

It is clear that change from a linear economy towards a circular economy is obligatory therefore; the futuristic biorefinery platform should have an ambitious vision to promote a switch from the consumption of fossil reserves to renewable or "green" resources (Mohan et al., 2016). This will contribute in mitigation of GHG emissions and its impact on climate change. Also, it will lead to incredible employment opportunities in industries and academia especially in the sectors of agri, food, chemical and healthcare, pharma and logistics (Amulya et al., 2016; Clark & Deswarte, 2015).

Bio-refineries are highly energy-efficient and make use of mostly zero-waste production processes, and they allow industries to manufacture environmentally friendly products with small carbon and water footprints. Therefore, a bio-refinery should be able to produce a gamut of marketable products and energy in a sustainable fashion (Gravitis, 2008). The design of a bio-refinery should be sustainable by taking into account possible unintended consequences such as the competition with biomass and other raw material resources, water usage, quality of the products, usage of land, emission of GHGs and impact on biodiversity (Van Dael et al., 2014).

11 Challenges and future perspectives

The development of waste-to-biopolymers processes can be more complex than their conventional counterparts. Implementation of such technologies requires collaboration of different stakeholders from waste generation, collection, conversion, production and distribution of final product and the interaction of different sectors could derive various mismatch issues. For example, waste is generated in a primary process and its amount or characteristics is different which is required for its conversion in the secondary process (Fernandez-Dacousta 2018). Therefore, cross sectors connection, capitalising knowledge and information and territorial flow (nutrient, material and energy) analysis is required.

These technologies can still generate waste and cascading the waste stream in the series of the production process to maximize the reuse of the waste streams is highly required and still lacks exhaustive research. Management of materials is required to address the inappropriate and unbalanced nutrient flow, contaminants accumulation and waste conversion issues. Also, the biomass feedstock expense may be intensified with the fostered attraction in bio-based polymers, hence, sustain of policy context that forfeits the practice of petrochemicals (with elevated influence on pollution and climate alteration) is vital to develop the market accomplishment of justifiable PHAs.

Nowadays, the crucial energy sources for the commercialisation of PHA production are till date glucose derived from food and vegetable oils. The utilization of hydrocarbon taken from waste plastics is yet limited till lab scale, although auxiliary experimentations should be directed to progress its profits and throughput. The usage of waste by-products from bio refinery, incorporating glycerol and lingo cellulosic sugars, is an assuring channel for sustainable manufacture of PHAs. Till date no wide-ranging economical methodologies have been acquired to entirely exploit fermentable sugars derived from lignocellulose. Bio refineries are an evolving perception for the industrialised commercial-scale lingo cellulosic by-product to develop biofuels and service platform chemicals. The by-products from the bio refinery consisiting of crude glycerol, hemicellulose hydrolysates, waste plant oils and low-grade biodiesels will be possibly sustainable raw materials for PHA production, nevertheless supplementary experimentations and studies are required to classify elevated yielding strains and optimum expansion situations to progress the profits and yielding capacity of PHAs for competent transformation. Amalgamation of PHA production in bio refineries will unwrap a fresh trail in the direction of producing bioplastics and counterpoise the elevated amount of the bioethanol and biodiesel. By positioning production of PHA keen on the context of a bio refinery, it will permit the bio refinery industry to generate both unique biopolymers and biofuels, similar to the prevailing petroleum-based final and furnished products.

Often the research experimentations do not contemplate the complete production chain encompassing the cost-effective, environmentally friendly, industrial and proper characteristics. It will not be feasible to estimate the sustainability of PHA in contradiction of its petrochemical adversaries and will be confusing if the greater sustainability is contemplated unbiased for their biodegradability. The foremost essential hold-ups of bio-plastics production developments interrelated to energy utilization, de-toxification experimentation, intricacy and inconsistency in the configuration of waste feedstocks, existence of contaminants, consumption of toxic chemicals, high production price and social insight (Gontard et al., 2018).

In past, the approaches were primarily directed on a definite source and its transformation into final product. Cross-chain valorisation of sewage, by-products, energy and water consumption is stimulating as a consequence of factors like heterogeneity of resources, disparity in the volume over time, batches, regions, mixture of existing alterations and consumption sectors. Control and reutilizing of by-product stream are massive and convey substantial charges and huddling of diverse construction sequences are vital to create widespread valorisations achievable. There is even now fewer alertness of valorisation prospects in assembled sets that instigates an encounter in suitability for customers. Furthermore, business replicas are desired to construct a circumstantial where all parties concerned can acquire a ‘win-win’ state (Gontard et al., 2018).

The usage of bioplastics in customer goods business could be yet called as 'playing in the dark' as numerous problems and their results are stuck in the investigation phase. An environmental and inexpensive achievement of bio-plastics will necessitate an initial and significant evaluation throughout the expansion of activity to ascertain and prevent "hotspots" that are dependable for compromising sustainability. Furthermore, sustainability is an advancing matter and individuals have to remould their methodology with respect to sustainability concerning bioplastics in the future. It is essential to discover an equilibrium amid the usage of biomass, among its financial valorisation and improving and/or maintaining the ecosystem comprising water quality, soil quality, biodiversity and availability.

The improved convolutedness in the development of bioplastics could challenge the necessity of rising prerequisite for biomass as the bio economy raises added consequently, determining the opposition amid plentiful biomass requests, escalating the sustainable produce and diminishing the environmental influences. Counting the circular hypothesis and ideologies in the arrangement, undesirable externalities of the prevailing bio economy could be talked by cultivating nutrient and energy equilibrium along with preserving the biological and technical material distinct. Though, bioplastics division is yet not entirely assimilated in the bio-economy traits up till now. Endeavours in experimentations and expansion, business forming, techno-economic outlines, sustainability evaluation are essential to support incorporation and widespread transformation into circularity.

12 Conclusion

Circular bioeconomy is one of important principles of economic policy and bioplastics produced using waste substrates fit perfectly in the concept. In addition to production using wastes substrates, sustainability assessment has to be carried out with respect to environment and economy. The thought of "Zero Emission" in the PHA production process can be highly beneficial in moving a step closer towards sustainability. However, more comparative studies are required for the entire PHA production process from raw materials to the final consumer selling form of the product, considering waste streams and recycling at each step.

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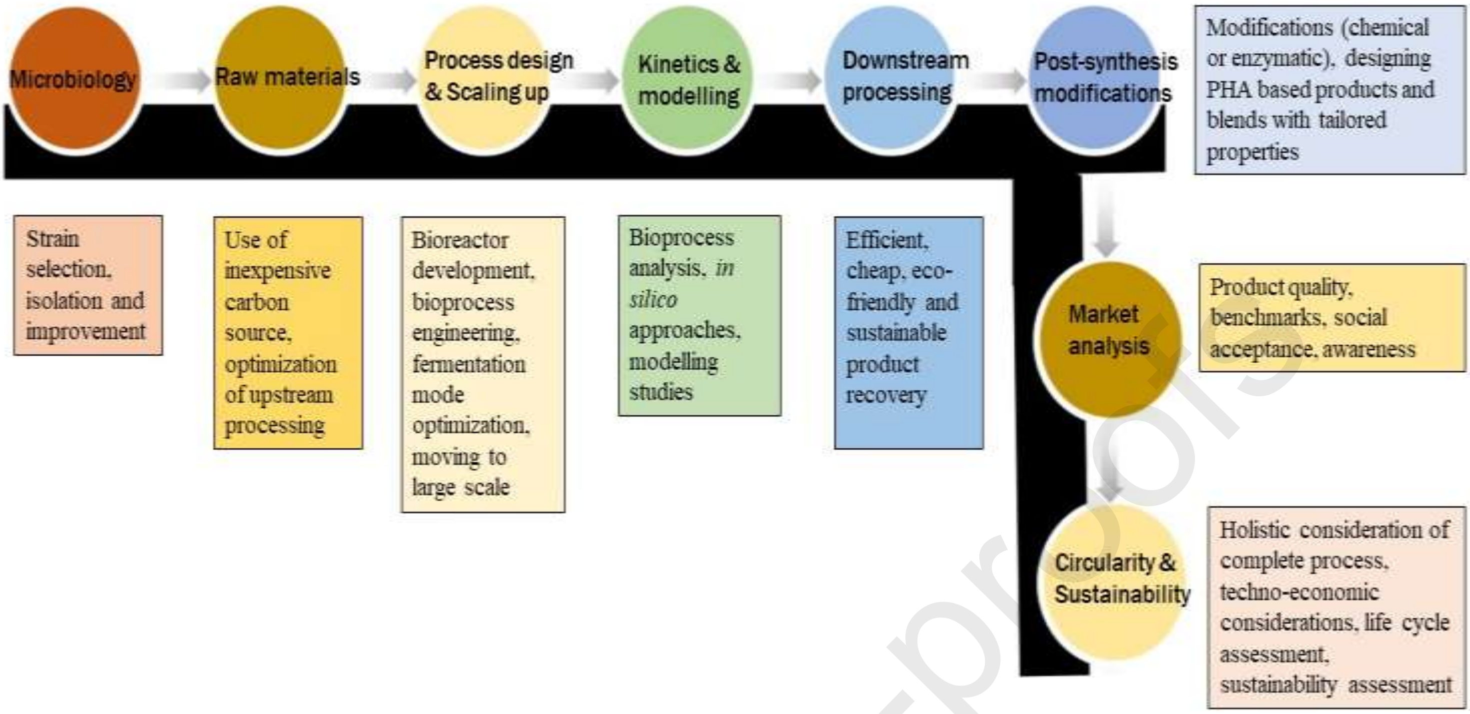

Figure 1: Steps to achieve the 4 'e'- Economic, Ethical, Environmental and Engineering aspects for a cost-effective and sustainable PHA production process

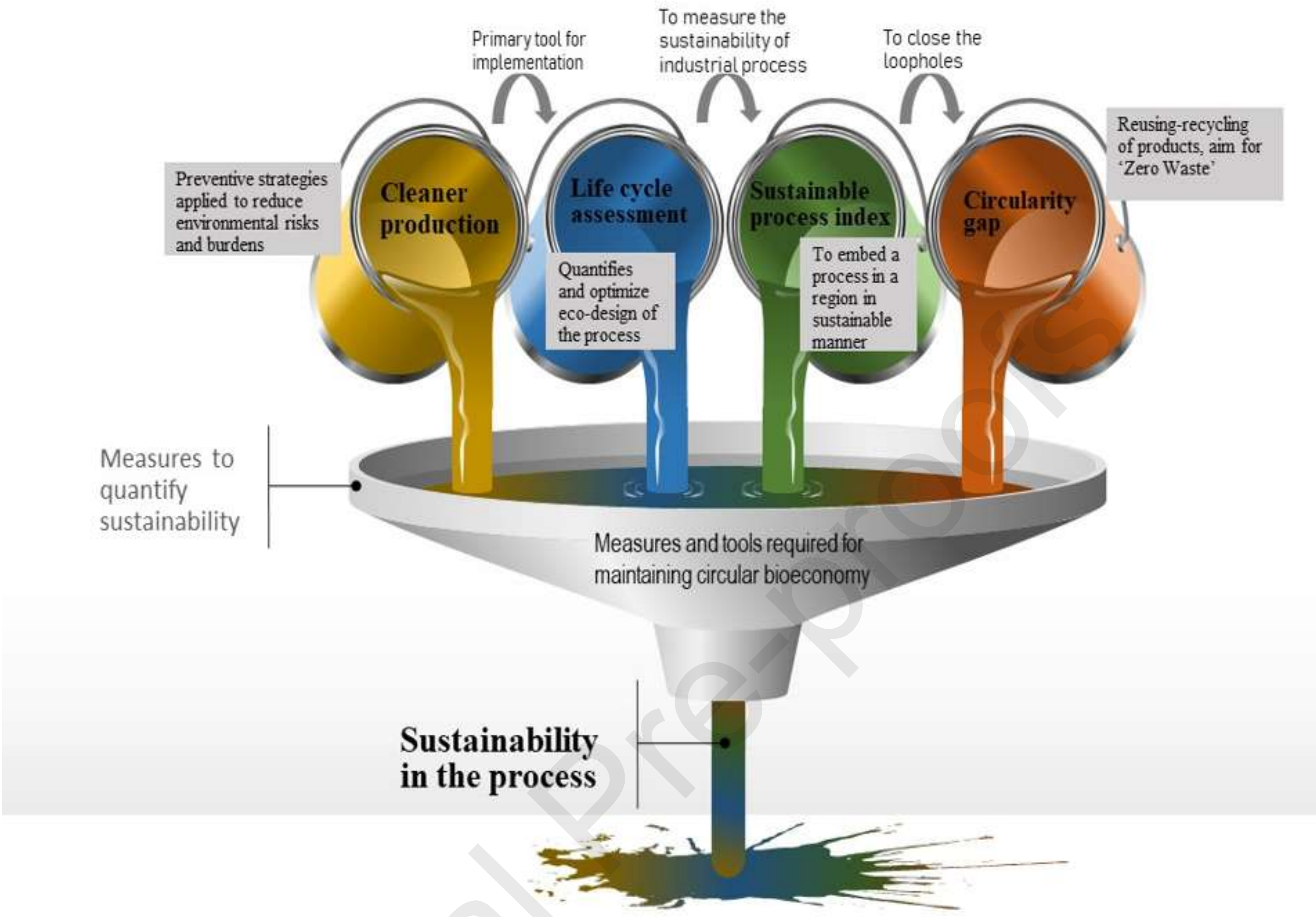

Figure 2: Tools to achieve eco-sustainability and their connections with each other that can be applied to PHA production process.

Table 1: Worldwide used bioplastics, their properties and their market status

Polymer	**Derivative source(s)**	**Properties**	**Commercial use(s)**	**Industry(s)**	**Reference (s)**
Biobased PE	Crude oil, natural gas, methane (after dimerization) and ethanol (derived from sugarcane)	Composition and performance are similar to petroleum-based PE; recyclable but non-biodegradable and helpful in reducing carbon dioxide levels.	Packaging, hygiene and medical applications.	Braskem, Brazil; Dow Chemical and Mitsui, Brazil	(Kawaguchi et al., 2017; Kim et al., 2019)
Biobased PET	Sugarcane-derived ethylene	30% bio based (bulk), recyclable in the flow of petroleum-based PET, rigid, transparent and food safe.	Rigid packaging for bottles, containers, pots and boxes; flexible packaging: film; and can be used as Fiber and in automobile industry.	Annellotech, New York; NaturALL Bottle Alliance, USA; Coca-Cola Company; PepsiCo Inc.; Toyota Tsusho Corporation; M&G Chemicals SA; Origin; Ford Motor Company; Teijin Limited	(Fiorentino et al., 2017; Mukherjee et al., 2019; Sara et al., 2016)
Biobased PU	Castor oil (Best suited), peanut oil, canola Oil and soya bean oil.	Abrasion resistant, supports chemical resistance, is flexible during cold temperature, UV and hydrolysis resistant, transparent and provides mechanical properties.	Formulations of reactive polyurethane hot-melts (HMPUR) used in furniture, automotive, textile, book-binding, and footwear, textile coatings for shoe stiffeners (toe puffs & counters), molded parts for various market segments, such as footwear, automotive, industrial, consumer electronics, and recreation.	BASF SE, Covestro AG, DowDuPont, Huntsman International LLC, The Lubrizol Corporation	(Haponiuk et al., 2017; Kawaguchi et al., 2017)
Bio based PC	Isosorbide derived from hydrogenation of glucose and then double dehydration of sorbitol.	Temperature resistance, impact resistance and optical properties.	Automotive, building & construction, Aircraft components, electrical & electronics, optics, security components and medical Applications.	Mitsubishi, Chemical Holdings Company and Teijin Limited.	(Jonker et al., 2019)
Polylactic acid	Lactic acid extracted from corn starch; sugarcane, and tapioca.	Degrade into nontoxic products, amorphous glassy polymer to semi-crystalline and highly crystalline polymer with a glass transition of 60 °C, melting temperature 173–178 °c, tensile modulus of 2.7–16 GPa and basic mechanical properties	Used for yogurt cups, is being used as a feedstock material in desktop fused filament fabrication 3D printers and used currently for medical implants in the form of anchors, screws, plates, pins, rods, and as a mesh.	Nature Works, Purac and Teijin.	(Pan et al., 2016)

		of PLA are between those of polystyrene and PET.			
PHA	Sugars derived from waste streams of different industries and Lipids	Good barrier properties, fully biodegradable in soil, water, and compost, good printability, good resistance to grease and oils and can withstand boiling water (HDT >120).	Biomedical uses, injection molding grades, packaging, denitrification agents for aquariums, cosmetics and scaffolds for tissue engineering.	Newlight Technologies, USA; Biomer, Germany; Polyferm Canada, Canada; Danimer Scientific, USA; Kaneka Corporation, Japan; Bio On, Italy and Tianan Biologic, China.	(Anburajan et al., 2019; Mannina et al., 2019)
Thermoplastic Starch	Sorbitol, Glycerol and Cashew nut shells	Flow at elevated temperature and pressure and can be extruded to give both foams and solid molded articles and thermoplastic-like process ability with temperature and shear.	Ballpoint pens, cutlery, packaging, bags, can also be used as a paper and production of drug capsules.	Novamont and BASF SE	(Jiménez et al., 2016; Wu et al., 2019; Zaaba & Ismail, 2019)

PE : Polyethylene, PET : Polyethylene terephthalate, PU: Polyurethane, PC: Polycarbonates, PHA: Polyhydroxyalkanoates, HMPUR : Reactive polyurethane hot-melt UV : Ultra - violet

Table 2: Commercial production of PHA globally

Company's name	**Country**	**PHA Product and it's trade mark**	**Application(s)**	**Product type**	**Microbial strain**	**References**
Biomer	Germany	Biomer	Extrusion and injection moulding	P3HB	n.r.	(Chen, 2009)
Polyferm Canada	Canada	VersaMer	Plastic Additives, adhesives, paints and coatings, inks and toners and biomedical.	mcl-PHA	*Aeromonas hydrophila*	(Tan et al., 2014)
Danimer Scientific	USA	Nodax	Packaging, laminates, coatings, non-woven fibres.	PHB	n.r.	(Amelia et al., 2019)
Kaneka Corporation	Japan	AONILEX	Electrical components, mulch films, composite bags and automotive.	PHBH	n.r.	(Wang et al., 2016)
Tianjin GreenBio Materials	China	Sogreen	Makes resin	P3HB-co-4HB	n.r.	(Rivero et al., 2017)
Tepha Inc	USA	TephaFLEX	Used in medical devices like sutures, films, and for textile products.	P4HB, P3HB-co-4HB	*Escherichia coli*	(Suriyamongkol et al., 2007)
Tianan Biologic	China	ENMAT	Injection moulding, extrusion thermoforming, blown films.	PHBV	*Cupriavidus necator*	(Verlinden et al., 2007)
Bio On	Italy	Minerv	Used in cosmetics such as lipstick, lip gloss, mascara, eye-liner, nail polish, creams, shampoos, shower gels and toothpastes.	n.r.	n.r.	(Tan et al., 2014)

n.r.-not reported, P3HB: Poly(3-hydroxybutyrate), mcl-PHA: Medium chain length polyhydroxyalkanoates, PHB: Polyhydroxybutyrate, PHBH: Polyhydroxybutyrate–hexanoate, P3HB-co-4HB: poly(3-hydroxybutyrate-co-4-hydroxybutyrate), P4HB: Poly-4-hydroxybutyrate, PHBV: Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

Table 3: PHA production from different waste streams

Waste stream	Substrate(s)	Strain(s)	PHA type	PHA content(%)	PHA Yield [g PHA) (g substrate)$^{-1}$]	CDW (g/l)	References
Biofuel Industry	Glycerol and trace elements	*Cupriavidus necator*	P(3HB)	62	0.38	82.5	(Rocha Jr, 2005)
	Glycerol liquid phase	Unidentified osmophilic organism	P(3HB-co-3HV)	76	0.50	n.r.	(Koller et al., 2005)
	Solid biodiesel waste added with molasses	*Cupriavidus necator*	P(3HB)	13.6	n.r.	68.8	(Rocha Jr, 2005)
	Crude glycerol	*Ralstonia eutropha ATCC17699*	P(3HB)	55	n.r.	7.5	(Gözke et al., 2012)
		Bacillus sphaericus NII 0838	P(3HB)	31	n.r.	2.8	(Sindhu et al., 2011)
		Pseudomonas oleovorans NRRL B-14682	P(3HB)	38	n.r.	2.7	(Ashby et al., 2011)
		P. oleovorans NRRL B-14682	PHB	27	0.13	2.5	(Ashby et al., 2004)
		E. coli CT106	P(3HB)	51	0.40	n.r.	(Nikel et al., 2008)
	Pure glycerol	*B. megaterium OU303A*	P(3HB-co-3HV)	62.4	n.r.	n.r.	(Reddy et al., 2009)
Pulp-Paper Mill	Hardwood spent sulfite liquor	Mixed microbial culture	PHA	67.6	n.r.	n.r.	(Queirós et al., 2014)
	Sludge from cardboard industry	*Enterococcus sp. NAP11*	PHB	79.27	n.r.	5.236	(Bhuwal et al., 2013)
		Brevundimonas sp. NAC1	PHB	77.63	0.25	4.042	(Bhuwal et al., 2013)
	Activated sludge with sodium acetate	n.r.	PHA	43.06	n.r.	n.r.	(Yan et al., 2006)
	Activated sludge	n.r.	PHA	48	n.r.	n.r.	(Bengtsson et al., 2008)
Dairy Industry	Whey	*Haloferax mediterranei*	PHBV	66	0.38	10.91	(Koller, 2015)
				53	0.49	7.45	(Pais et al., 2016)
		Thermus thermophiles HB8	PHV and mcl- PHAs	35.6	n.r.	1.60	(Pantazaki et al., 2009)

		Unidentified osmophilic organism	PHBV	10	n.r.	n.r.	(Koller et al., 2005)
		Bacillus megaterium CCM 2037	PHB	51	0.11	2.87	(Obruca et al., 2011)
		Alcaligenes eutrophus	PHB	76	0.33	5.28	(Berwig et al., 2016)
		Plasticicumulans acidivorans	PHA	70	n.r.	n.r.	(Tamis et al., 2014)
		Hydrogenophaga pseudoflava	PHB	40	n.r.	4.1	(Povolo & Casella, 2003)
		Methylobacterium sp. ZP24	PHB	59	n.r.	n.r.	(Nath et al., 2008)
		Haloferax mediterranei	PHB	50	n.r.	12.2	(Koller et al., 2007)
	Whey permeate	*Cupriavidus necator mRePT*	PHB	25	n.r.	8	(Povolo et al., 2010)
Food Industry	Cassava starch	*Cupriavidus sp. KKU38*	PHB	61.6	0.23	9.69	(Poomipuk et al., 2014)
	Spent coffee grounds oil	*Cupriavidus necator DSM 428*	PHB	78.4	0.34	16.7	(Cruz et al., 2014)
		Cupriavidus necator H16	PHB	89.1	0.40	55.4	(Obruca et al., 2014)
	Wheat straw	*Burkholderia sacchari DSM 17165*	PHB	72	0.36	n.r.	(Cesário et al., 2014)
	Wheat bran	*Halomonas boliviensis LC1*	PHB	34	n.r.	1.08	(Van- Thuoc et al., 2008)
	Bean curd waste	*Alcaligenus latus*	PHB	66.56	n.r.	3.73	(Kumalaningsih et al., 2011)
	Rice- based ethanol stillage	*Haloferax mediterrranei*	PHBV	71	n.r.	23	(Bhattacharyya et al., 2014)
	Sugarcane vinasse	*Haloarcula marismortui*	PHB	23	n.r.	12	(Pramanik et al., 2012)
		Haloferax mediterrrane	PHBV	70	n.r.	28.1	(Bhattacharyya et al., 2012)
	Rice straw	*Bacillus firmus NII 0830*	PHB	89	0.33	n..r.	(Sindhu et al., 2013)
	Oil palm empty fruit bunch	*Bacillus megaterium R 11*	PHB	51.6	n.r.	24.29	(Zhang et al., 2013)

n.r.-not reported, P(3HB): Poly(3-hydroxybutyrate), mcl-PHA: Medium chain length polyhydroxyalkanoates, PHB: Polyhydroxybutyrate, PHBV: Poly(3-hydroxybutyrate-co-3-hydroxyvalerate), P(3HB-co-3HV): poly(3-hydroxybutyrate-co-3-hydroxyvalerate), PHV: Polyhydroxyvalerate

Highlights

- Waste substrates or recycling of waste stream reduce cost and energy input for PHA production
- Recycling of waste streams and residual biomass has closed the gap in the circularity of the system
- Social and political factors need to be considered for effecting implementation of circular bioeconomy

Graphical abstract